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Analysis of the design and economics of molten carbonate fuel cell tri-generation systems providing heat and power for commercial buildings and H_2 for FC vehicles

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HIGHLIGHTS

- Model operation.
- Efficiency accounting methods.
- Economically competitive.

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ABSTRACT

This study models the operation of molten carbonate fuel cell (MCFC) tri-generation systems for “big box” store businesses that combine grocery and retail business, and sometimes gasoline retail. Efficiency accounting methods and parameters for MCFC tri-generation systems have been developed. Interdisciplinary analysis and an engineering/economic model were applied for evaluating the technical, economic, and environmental performance of distributed MCFC tri-generation systems, and for exploring the optimal system design.

Model results show that tri-generation is economically competitive with the conventional system, in which the stores purchase grid electricity and NG for heat, and sell gasoline fuel. The results are robust based on sensitivity analysis considering the uncertainty in energy prices and capital cost. Varying system sizes with base case engineering inputs, energy prices, and cost assumptions, it is found that there is a clear tradeoff between the portion of electricity demand covered and the capital cost increase of bigger system size. MCFC Tri-generation technology provides lower emission electricity, heat, and H_2 fuel. With NG as feedstock the CO_2 emission can be reduced by 10%–43.6%, depending on how the grid electricity is generated. With renewable methane as feedstock CO_2 emission can be further reduced to near zero.

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1. Introduction

Zero emission vehicle (ZEV) technologies could play an important role in enabling a low carbon future. Currently available ZEV technologies are hydrogen fuel cell electric vehicles (FCV) and battery electric vehicles (BEV). As major automobile companies are now making BEVs available in the market, and FCV introduction is slated from 2013 to 2015, questions such as how to provide sufficient and convenient refueling infrastructure for these vehicles become imperative.

The lack of hydrogen refueling infrastructure remains as one of the major barriers to an FCV rollout. In many cases fuel suppliers are hesitant to invest in early hydrogen refueling stations, even with partial public funding, due to high initial costs and low and uncertain hydrogen demand in the near term [1].

Emerging technologies such as fuel cell tri-generation systems have the potential to improve the economics of hydrogen transportation fuel by co-producing three valuable products: electricity and heat for buildings, and hydrogen for vehicles. Tri-generation systems are not commercially available, but several demonstrations are underway in the US, Japan and Europe, and system designs and analyses have been studied with various configurations [2]. A typical tri-generation system design produces electricity and heat for buildings as well as hydrogen for vehicles by converting a hydrocarbon such as natural gas (NG) or bio-methane [3]. Low

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utilization that is normally associated with early hydrogen refueling stations is not likely to be a problem, since a tri-generation system can always produce electricity and heat regardless of the size of the H_2 demand. In addition, a tri-generation system may generate less criteria air pollutant and CO_2 emissions compared with the business as usual (BAU) cases for separately producing the three energy products (i.e., grid electricity, NG heat, and gasoline) due to higher efficiency and no combustion [4]. If bio-methane is used as feedstock, tri-generation would lead to near zero CO_2 emissions.

The objective of this study is to model the operation of commercial building tri-generation systems for "big box" store businesses such as Safeway and Costco, which are a combination of grocery and retail business, and sometimes gasoline retail. The reasons for considering these stores are summarized in Section 2. This study is part of our ongoing research efforts to identify viable, novel and low risk strategies to provide low-cost hydrogen refueling for FCV rollout, with a focus on distributed production technologies [5,6].

2. Background

Our previous research on neighborhood scale tri-generation in residential areas indicates that the technology is technically available and economically promising from a consumer's perspective based on life cycle cost analyses [5–7]. Commercial building tri-generation systems have some additional attractive features compared with residential tri-generation systems:

- Commercial buildings generally have higher load factors for electricity and heat (i.e., less peaky load profiles) than residential buildings. This often means the economics of co-producing electricity and heat is better for commercial buildings because the tri-generation system is better utilized.
- Commercial building tri-generation systems are often at a scale of a few hundreds of kW, which is significantly higher than a home or neighborhood system. Better economies of scale can be achieved.
- Big box grocery and retail stores such as Costco and Safeway often have very large parking areas and could provide space for a refueling station for FCV users to refuel. Some of these stores already have gasoline refueling stations.
- Big box grocery and retail stores are attractive sites for other consumer activities; consumers frequently combine shopping trips with refueling to these stores when fueling stations are available at the stores.
- Big box grocery and retail stores are conveniently located in high volume traffic areas (shopping centers), and could provide fast public refueling capabilities to complement home hydrogen refueling. Commercial building tri-generation systems might compete directly with early public H_2 stations and neighborhood refueling facilities.
- Some big box grocery and retail stores have already invested and have experience in renewable energy and transportation fuel retail. They may be more willing to invest in H_2 infrastructure than gasoline station owners, if tri-generation is proven to be promising in terms of reducing building energy costs for electricity and heat while providing new revenue from hydrogen sales.
- Demand charges for commercial electricity can be a significant part of the cost of electricity for commercial buildings and reductions in these demand charges due to peak shaving using a tri-generation system may contribute to the economics of the entire system.
- Tri-generation onsite also enhances the reliability of the energy systems of the stores in the form of backup power in case of outages or emergencies. This may be of value to grocery stores, which may continue to serve customers and reduce loss from food spoilage in case of power outages.

The fuel cell industry is now beginning to pay attention to tri-generation technologies. Some companies that have traditionally made combined heat and power co-generation systems have started to try to modify their existing products to offer tri-generation models [8]. However, it wasn't until recently that fuel cell developers and government agencies started to seriously consider tri-generation technologies [9]. Many important questions remain unanswered. The following is a list of example questions relevant to this study.

- What are the electricity, heat, and refueling energy demands for the businesses under consideration?
- What are the design (optimal sizes) and costs for a commercial building tri-generation system designed to meet these energy demands?
- What is the best operating strategy for the tri-generation system? For example, previous research concluded that an exact match of electricity and heat demand would allow better utilization of co-generation/tri-generation systems and thus higher overall efficiency and better economic performance [10]. Prior research suggests achieving this match of demand by operating the system as heat-following [11]. However, in many applications the heat demand is significantly lower than electricity demand. A heat-following strategy would only provide a small portion of total electricity demand. What is the impact on the economic performance of a tri-generation system when operating as electricity load following vs. heat load following?
- How do the costs of providing electricity, heat, and H_2 compare for a commercial building tri-generation system and a Business as Usual (BAU) system (a combination of grid electricity, heat provided by conventional NG heating system, and gasoline retail). Under what circumstances do tri-generation systems compete with BAU systems?
- How does the cost vary with the number of FCVs using the station? Does the power and heat production make small H_2 refueling stations more competitive, and to what extent?
- Would tri-generation represent a promising investment for the businesses, given the potential for energy cost saving and H_2 sales income?
- What is the potential for commercial tri-generation in terms of local electricity grid support such as for concentrated BEV deployment in early adopter communities?
- How do the emissions of green house gases (GHG) and criteria pollutants compare to other energy supply options?

This study aims at providing insights into these questions using representative energy demand data for the businesses under consideration and recent engineering inputs and cost data on tri-generation systems from the fuel cell industry. By including small capacity hydrogen fuel production (supporting around 100 vehicles at full capacity) via commercial tri-generation in the discussion, this study fills an important gap in the research and analysis of hydrogen refueling infrastructure development.

3. Methodology and procedure

Building upon our previous research on residential tri-generation systems, detailed modeling and analysis of commercial building tri-generation systems for grocery and retail stores such as Safeway and Costco are conducted. The analytical tools utilized include an interdisciplinary framework and the HTS model (H_2 tri-generation systems model) [5–7].

The interdisciplinary framework uses a combination of process engineering modeling, engineering/economic modeling, cash flow analysis, business analysis techniques, full fuel cycle economic and emission analysis, demand side management, and policy analysis.

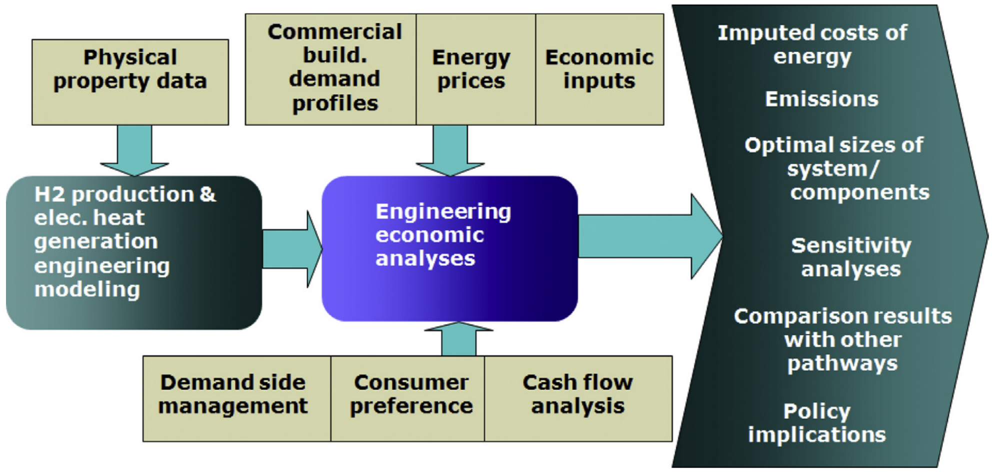

Fig. 1. Interdisciplinary framework for analyzing tri-generation systems (modified from source: Ref. [5]).

Fig. 1 illustrates the interdisciplinary framework for analyzing a FC tri-generation system.

The HTS model consists of two main stages: first, the engineering modeling for the operation of the tri-generation system; second, the economic analysis of installing and operating the system. In the first stage, the engineering modeling is implemented through a dynamic process model based on energy and material balance. In the second stage, economic analyses are conducted on the basis of the engineering performance inputs from the first stage, cost data, and other economic inputs; environmental cost information can be integrated into the modeling process as well.

To assess the system economics, we estimate the levelized cost of energy products (electricity or hydrogen) for a system of a specific size. The levelized cost of energy products is the price at which an energy product must be generated from a source to breakeven, accounting for the present value of all cost and credits over the life time of the system. The levelized cost of energy products is an assessment of the life time cost of the energy system including capital cost, maintenance and operation cost, and feedstock cost. It is useful in comparing the cost of different energy systems.

The major steps of the modeling and analysis using the HTS model are summarized as follows:

1. Start with representative commercial grocery/retail building and determine the hourly profile of electricity, heat and hot water demands for an entire year.
2. Select system component sizes including FC stack and other component sizes in order to calculate all life time costs such as capital cost and feedstock cost. The average hourly demand can be a start point.
3. If the system is not sized to be large enough to meet all energy demands, it is possible to purchase electricity and NG (for heat) from utilities to cover any shortfall.
4. Once the analysis is conducted using inputs such as the energy demand data, engineering efficiency inputs, and energy prices, we can obtain the levelized cost of energy products.
5. The CO_2 emissions from the tri-generation system can be calculated as well.
6. The levelized cost of electricity and CO_2 emissions of the tri-generation system can be compared with the grid electricity price and CO_2 emissions of the BAU case of purchasing grid electricity and heat while selling H_2 at a price that is equivalent to the price of gasoline (on a $ per mile basis).
7. Alternatively, by assuming values for electricity and heat, we can calculate a levelized cost for H_2 fuel which can be compared with the H_2 cost from public fuel only H_2 stations and other refueling facilities.
8. If we iterate through many different system sizes using a brute force exhaustive search algorithm around the range of electricity load, we can find the optimum system size which gives us the lowest life time system costs, or lowest levelized energy cost; We can analyze system sizes in a couple of ways. One is to fix H_2 price and calculate the levelized cost of electricity. The other is to fix the electricity price and calculate the levelized H_2 cost. These two approaches give the same outcome in terms of optimum system size.

Equation (1) is used in the HTS model to calculate the levelized cost of electricity (LEC) from the owner's perspective [5]. When calculating the LEC, credits are taken for heat and transportation fuel co-produced by the tri-generation system. The credit for heat is based on what it would have cost to provide heat using a conventional NG combustion based system. The credit for transportation fuel is based on how much income it would have brought by selling hydrogen at a market price that is equivalent to gasoline on a $ per mile basis.

The LEC can be compared to the price of grid electricity, and the levelized cost of hydrogen can be compared to the price of gasoline fuel, as a metric for when the tri-generation system is competitive with the BAU case.

$$\overline{R}_{\mathrm{elec}} = \frac{\mathrm{CRF} \times (\mathrm{CC} - C_{\mathrm{credit}}) + C_{\mathrm{o\&m}} + \int R_{\mathrm{NG}} n_{\mathrm{NG}} \mathrm{d}t - \int R_{\mathrm{ele}} (P_{\mathrm{FC}} - P) \mathrm{d}t + \int R_{\mathrm{ele}} (P - P_{\mathrm{FC}}) \mathrm{d}t + R_o - c_{\mathrm{heat}} - c_{\mathrm{transport}} - t_{\mathrm{carbon}}}{\int P \mathrm{d}t} \quad (1)$$

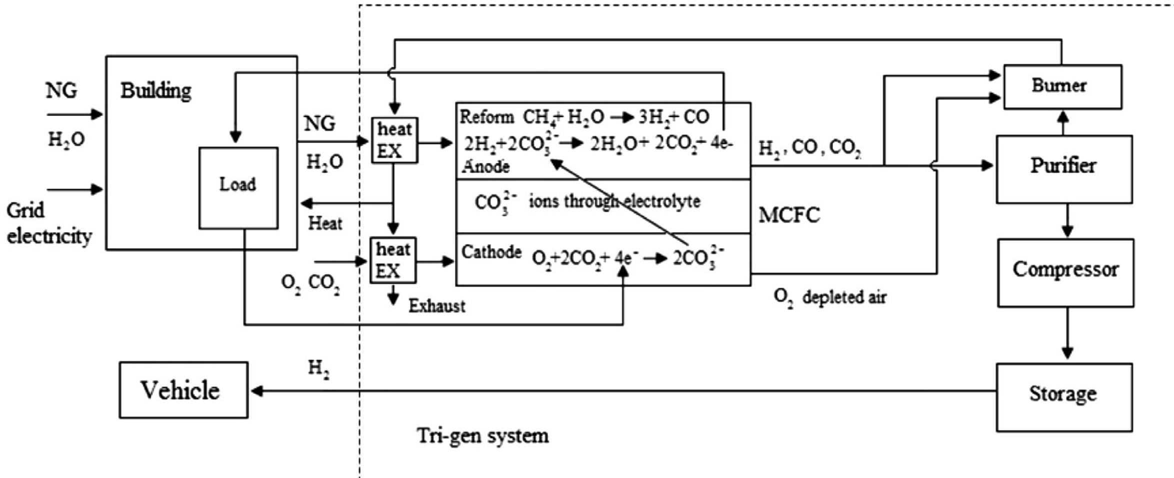

Fig. 2. Schematics of an internal reforming MCFC tri-generation system.

$\overline{R}_{elec}$ is the LEC (\$ kW h^{-1});

CRF is the capital recovery factor;

CC stands for the present value of life cycle capital cost of a system (\$);

C_{credit} represents various credits including feebate and tax credits (\$);

$C_{o\&m}$ is fixed annual operating and maintenance cost (independent of the amount of energy produced) including labor, maintenance costs, and overhead (\$ y^{-1});

R_{NG}, is the price of NG (\$ GJ^{-1}); n_{NG} is the annual amount of NG consumed (GJ y^{-1});

R_{elec} is the grid electricity price (\$ kW h^{-1});

P is the hourly average electricity demand load (kW), and $\int P\mathrm{d}t$is annual electricity demand (kW h y^{-1});

P_{FC} is the operating load of the fuel cell stack, $\int R_{elec}(P_{FC} - P)\mathrm{d}t$ is credit for exporting electricity to the grid, and $\int R_{elec}(P - P_{FC})\mathrm{d}t$ is the cost to buy electricity from the grid;

R_o represents other charges for electricity services such as access charge and demand charge; c_{heat} represents the annual credit of hot water and space heat, (based on what it would have cost to provide hot water and heat using conventional NG combustion based systems (\$ y^{-1})[1];

$c_{transport}$ represents the annual credit of transportation fuel (hydrogen), based on how much revenue it would have brought to the business selling H_2 based on a price equivalent to gasoline from a public refueling station (\$ y^{-1});

t_{carbon} represents annual carbon tax (\$ y^{-1}).

An analogous equation can be developed for levelized hydrogen cost by fixing the LEC of electricity generated by tri-generation systems to be the grid electricity price and re-arranging Equation (1). See Ref. [5] for further details on calculating the levelized cost of energy products and the HTS model.

The tri-generation system investigated in this study uses a Molten Carbonate fuel cell (MCFC), which is considered as a high temperature (850 K–1000 K, or 600–750 °C) fuel cell and internally reforms fuels such as NG or bio-methane [4,12,13]. The model can be modified easily for assessing other types of medium and high temperature fuel cells such as phosphoric acid fuel cells or solid oxide fuel cells [4,12,13]. Fig. 2 shows the schematics of the internal reforming MCFC tri-generation system under consideration.

4. Case study

4.1. Energy demand analysis

In this paper, we employ representative hourly electricity and heat demand profiles for a grocery and retail store in the northern California area served by Pacific Gas and Electric (PG&E), a large utility that provides electricity and NG. The electricity and heat demand data are provided by a consulting firm under a contract with the California Energy Commission (CEC) [14]. These CEC data are given in the form of aggregated electricity and heat demands for all grocery stores in the area for every hour of a year. An index of energy per square foot is also given in the CEC data. In our case study, we use this index to construct hourly electricity and heat demands over the entire year (8760 h year^{-1}) for a hypothetical 55,000 square foot store.[2] Figs. 3 and 4 show the hourly demand profiles of the store for two winter and summer days, respectively, as an example.

From Figs. 3 and 4, we see that there is high heat demand in the winter and low heat demand in the summer, and we will see that this has implications for the overall efficiency and economics of co-generation and tri-generation systems. High waste heat utilization normally means higher overall system efficiency and thus better economics, holding other factors constant.

The commercial building electricity load data includes lighting, refrigeration, air conditioning, and in some cases hot water and space heat (stores also use NG for how water and space heat). Because a tri-generation system provides both electricity and heat, we developed profiles for non-heat total electricity demand and total heat demand (hot water and space heat combined) for the analysis. The heat provided by electricity is subtracted from the original electricity profile to obtain an electricity profile excluding electricity for heat. Total heat consumption profile is developed by summing all the heat profiles provided by both electricity and NG. In Figs. 3 and 4, the "Elec_non_heat" curve is the profile derived by excluding the portion of electricity for hot water and space heat demand. "Hot water" curve is the profile of NG energy content for total hot water demand, sum of hot water heat provided by both electricity and NG.[3] "Space_heat" curve is the profile for total space

[1] Heat sometimes is provided by electricity. The assumption represents a conservative estimation of the cost of heat from conventional systems, because electricity is normally more expansive as a heat source without using heat pumps.

[2] The size of the store is chosen based on a survey of 13 grocery stores (brands include Costco, Safeway, Trader Joe's, and Target).

[3] The electricity to hot water heat efficiency is assume to be 100%, and the NG combustion based hot water system efficiency is assumed to be 80%.

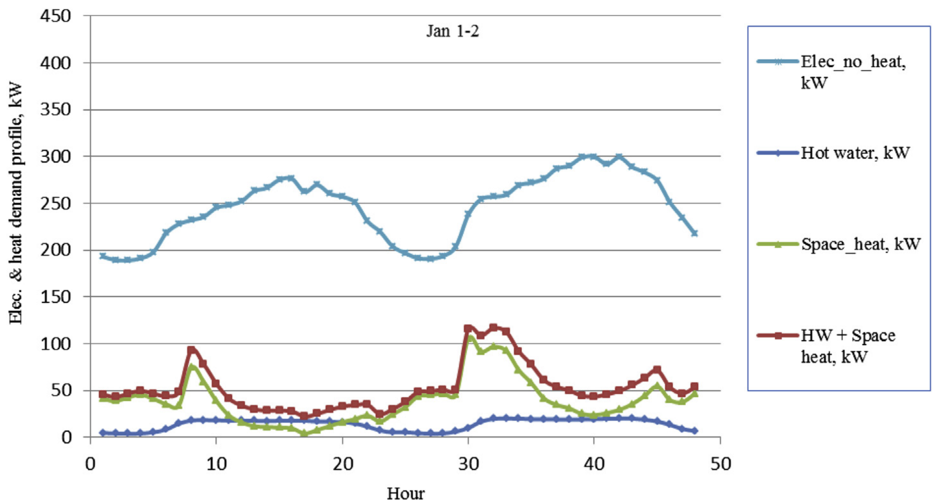

Fig. 3. Demand profile for two winter days.

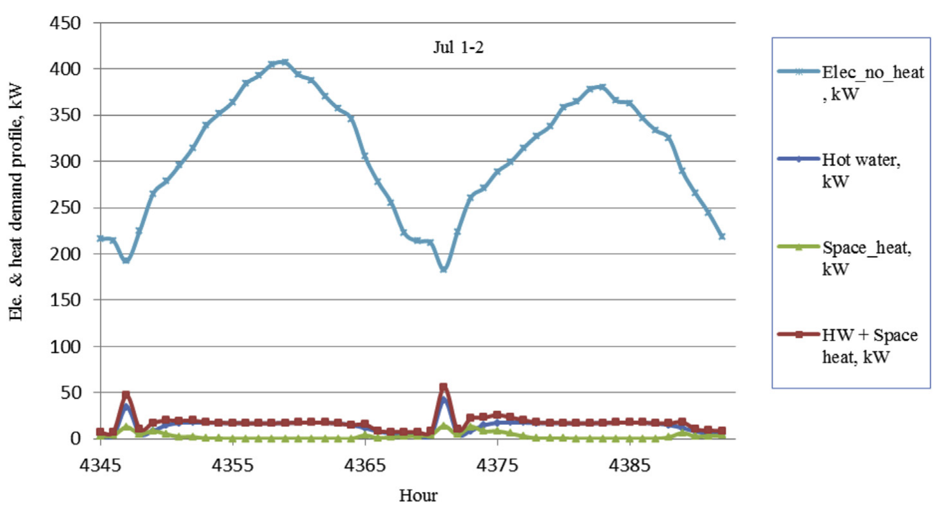

Fig. 4. Demand profile for two summer days.

heat demand, sum of space heat provided by both electricity and NG. “Hot water + space_heat” curve is the profile of NG energy content for total hot water plus total space heat demand.

As shown in Figs. 3 and 4, the daily hot water demand pattern is almost the same throughout the year. Space heat varies significantly with seasons, and peaks during the winter. In the summer, there is nearly zero space heat demand. The “Elec_non_heat” demand has significantly higher peaks in the summer than in the winter, probably due to higher air conditioning and refrigeration needs in the summer.

In this study, it is assumed that the tri-generation system is grid connected and enrolled in a Net Metering Program,[4] which allows the system to import and export electricity from and to the grid. Heat is a by-product of electricity generation. The statistics of the electricity and heat demand of the store under study is summarized in Table 1. The average hourly heat to electricity demand ratio is 0.14. This is very different from the energy demand pattern in residential buildings. Based on our previous study, the average hourly hot water heat alone to electricity demand ratio is 0.47 [7].

It is expected that the electricity generation process in the commercial building tri-generation system has more than enough waste heat to recover for providing both hot water and space heat throughout the year.

Similar to heat, H_2 fuel is a by-product of electricity generation process in MCFC tri-generation systems. Varying the fuel utilization rate in the MCFC can lead to different H_2 fuel production rates

Table 1
The statistics of energy demand (data based on 365 days) for a hypothetical 55,000 square foot grocery store.

Energy form	Hourly average power, kWh h^{-1}	Annual end-use energy consumption, kWh	Demand max, kW	Demand min, kW	Demand stdev, kW
Elec_ no_heat	276	2,413,963	414	90	54
Hot water & space heat	40 (144 MJ h^{-1}, 1.365 therm h^{-1})	352,812 (1270 GJ, 12,041 therm)	185	5	31

[4] Net metering is a program allowing customers with an eligible distributed generation system to offset their electricity cost with electricity they export to the grid. A “net meter” is normally installed to measure the difference between electricity the customer purchases and exports to the grid. Under Sec. 1251 of the US Energy Policy Act of 2005, “all public electric utilities are required to make available upon request net metering to their customers”.

Table 2
Main engineering inputs.

Gross electrical efficiency[a] [8,18]	47% (70% fuel utilization[b])
Parasitic loss (mechanical balance of plant including blowers)	14% of total DC power generated by the FC stack
Net electrical efficiency[c] [8,18]	40.4% (86% of total DC power generated by the FC stack)
Heat for internal reforming of NG	15% of the total NG energy input
Rate of heat recovery [19]	70% of the heat generated by the FC stack (excluding heat consumed by NG internal reforming) can be recovered for hot water and space heat
Heat loss to environment such as through pipes	30% of the heat generated by the FC stack excluding heat consumed by NG internal reforming
H_2 purification and compression efficiency	73% (85% of H_2 in the anode gas is recovered, and 12% of the hydrogen energy in the forms of heat and electricity is consumed to separate and compress H_2 for refueling vehicles [8])

[a] Gross electrical efficiency is the total DC power generated by the fuel cell stack divided by the portion of NG fuel input used for electricity generation. Parasitic power such as for blowers, compressors, control units is not excluded.
[b] Fuel utilization in this study ranges from 60% to 80%. 47% gross electricity efficiency is a conservative assumption for the fuel utilization range.
[c] Net electrical efficiency is the net AC power sent to the grid (taking into consideration the parasitic power) divided by the portion of NG fuel input used for electricity generation.

Table 3
Main economic assumptions and inputs.

Real discount rate	8%
Equipment life time	10 year (the FC stack needs to be replaced every 5 years, and the replacement cost is incorporated into the capital cost.)
Capital recovery factor (CRF)	0.149
Maintenance cost	It is assumed the system is remotely monitored 24/7 each week, with technicians on call to fix problems (This is current practice in the industry). Maintenance cost is calculated based on 20% down time and hourly rate of $70 per hour.
NG price[a]	$4.98 per thousand cubic feet ($0.49 $therm^{-1}$, $4.62 GJ^{-1}, or $0.0166 $kW\ h^{-1}$)
Gasoline price[b]	$4.1 $gallon^{-1}$ (equivalent to a $7.52 kg^{-1} price of H_2 on a $ per mile basis)[c]

[a] This is the NG price to electric power generation customers based on the California average price in 2012 as of July 2012, a 50% additional cost is added to account for additional potential distribution and delivery cost for commercial customers; later in sensitivity analysis we also use the commercial NG rate, which is higher (Energy Information Administration online data: http://www.eia.gov/dnav/ng/hist/n3045ca3m.htm).
[b] The yearly average of weekly average gasoline price in California as of July 3, 2012, from California Energy Commission online data.
[c] The fuel economy of a FCV is assumed to be 55 miles per kg of H_2, and the fuel economy of a gasoline car is assumed to be 30 miles per gallon.

relative to electricity generation rate. The price of H_2 fuel is assumed to be equivalent to gasoline fuel on a $ per mile basis. The fuel economy of a H_2 fuel cell vehicle is assumed to be 55 miles per kg of H_2, and the fuel economy of a gasoline vehicle is assumed to be 30 miles per gallon [6].

4.2. Engineering and economic inputs

Model results for tri-generation systems may vary significantly with engineering and economic inputs and assumptions such as efficiency loss of major system components and energy prices. Therefore, it is necessary to clearly define the efficiency accounting methods and main engineering and economic inputs. This is especially true in this study for a couple of reasons. First, MCFC systems co-produce three energy products and internally reform NG to H_2 and other chemicals, which makes calculating efficiency loss of all steps complex. Tri-generation is a relatively new technology; a literature review [2,15–17] shows that a clear and well accepted method for efficiency calculation has not been established yet. Second, the economics of installing and operating a tri-generation system is susceptible to the uncertainty in capital cost reduction, and NG to electricity price ratio.

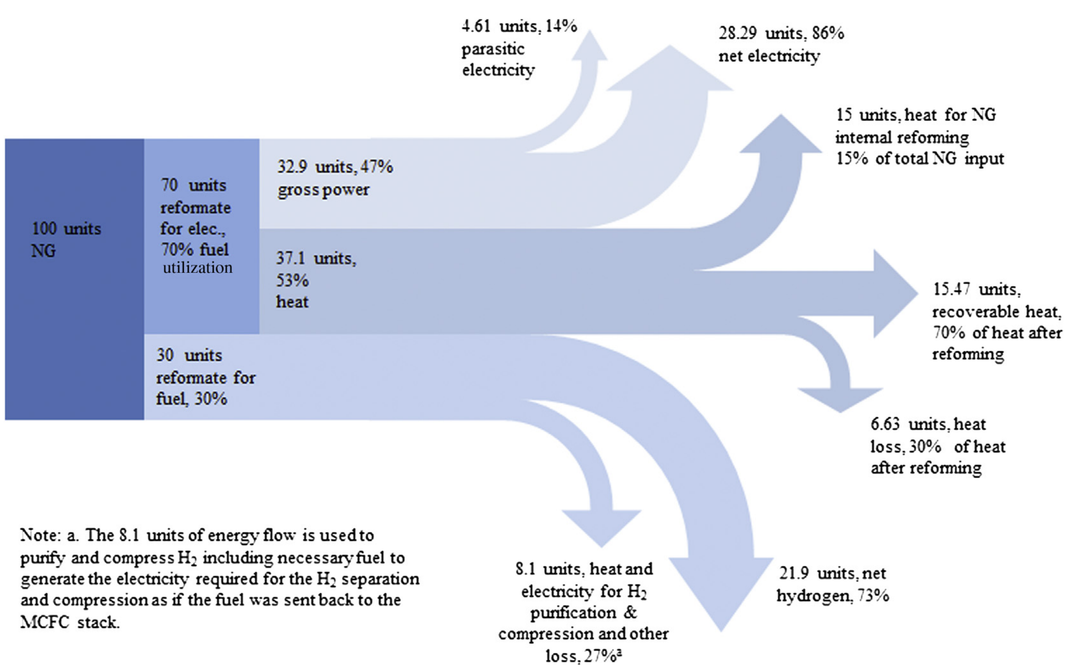

Fig. 5. The Sankey diagram of the energy flow of a MCFC tri-generation system with 100 units NG energy input (70% fuel utilization).

Table 4
PG&E A-10 electricity rate [20].

Rate schedule	Customer charge	Season	Demand charge (per kW)	Time-of-use period	Total energy charge (per kWh)
A-10 TOU	\$4.59959 per meter per day	Summer	\$11.35	Peak	\$0.13927
				Part-peak	\$0.13513
				Off-peak	\$0.11931
		Winter	\$5.84	Part-peak	\$0.10469
				Off-peak	\$0.09231

Table 2 presents main engineering inputs in this study. Fig. 5 is the Sankey diagram illustrating the energy flow of the MCFC tri-generation system based on the inputs in Table 2. From Fig. 5, we can see the overall net efficiency is 50.2% and 65.66% for electricity plus H_2, and electricity plus H_2 and heat, respectively.

Table 3 is a summary of main economic assumptions and inputs in this study. Table 4 shows the electricity rate adopted, which includes the demand charge and time of use rate. Table 5 presents the assumptions on system components cost. In Section 4.3, the cost details of a specific size system will be given as an example.

The component costs estimation is based on cumulative production volume ranging from 10 s to 100 s. Different components have different technology maturity, and different production volume. For example, compressors and storage system have a cumulative production volume over 100, while purifier and MCFC have a cumulative production volume of 10 s [21].

4.3. Operation strategy

Current MCFC systems are not designed to follow electricity loads. First, the high temperature of MCFC (850 K–1000 K, or 600–750 °C) requires hours for startup to avoid damage, and thus MCFC is only suitable for continuous operation with current technology. Second, the variation in temperature and pressure can significantly affect the performance of MCFC. With current technology, it is difficult to maintain the optimal temperature when the systems have to respond quickly to changes in electricity load [4,12,13]. Developers are not pursuing an electricity load following operation strategy for MCFC system for the time being. However, the actual electricity load for commercial buildings varies significantly throughout a day and with seasons. For the grocery store under study, the electricity demand ranges from 90 kW to 414 kW. If the system capacity is lower than 414 kW, the tri-generation system needs to be grid connected, unless the system is configured with a battery. For instance, for a 90 kW system, around 70% of total annual hourly electricity demand would need to be met by the grid or a battery. Allowing the MCFC systems to be switched to a couple of partial loads with reduced frequency may be a good tradeoff to reduce the mismatch in supply and demand.

Table 5
Assumptions on system component costs (in 2012 dollars).[a]

Component	Cost, \$
MC fuel cell	$=179{,}256.2 \times P_{max}^{1/3} \times 0.85$, (where, P_{max} is rated maximum power of the FC stack, 0.85 is production volume discount factor)
Co-generation heating system	$=200 \times P_{max}$, (where, P_{max} is rated maximum power of the FC stack)
H_2 purification (e.g., PSA unit)	$=87{,}058 \times (H_{purif}/4.167)^{0.5} \times (x/10)^{\ln(0.85)/\ln(2)}$, (where H_{purif} is the H_2 purification rate in kg h^{-1}, 0.5 is a size scaling factor, and 0.85 reflects production volume discount)
Storage system, cascade system	$=1026 \times (H_{store})^{1.081} \times a$, (where, H_{store} is hydrogen stored in kg, $a = 0.95$ is production volume discount factor)
Compressor	$=\$26{,}913 \times (P_{comp})^{0.5202} \times b$, (where P_{comp} is the Compressor flow rate in kg h^{-1}, $b = 0.91$ is production volume discount factor)
Dispenser	$=55{,}073 \times n \times c$, (where, n is the number of dispenser, $c = 0.77$ is production volume discount factor)
Electrical equipment	$=170.632 \times P_{max}$, (where, P_{max} is rated maximum power of the FC stack)
Safety equipment	$=40 \times P_{max}$, (where, P_{max} is rated maximum power of the FC stack)
Mechanical and piping	$=80 \times P_{max}$, (where, P_{max} is rated maximum power of the FC stack)
Maintenance cost	$=t_d/24 \times 8 \times m$, (where, t_d is the down time in hour, m is the hourly rate of maintenance service)
Non-equipment	12% of total capital cost (this is relatively lower than the rate in [21], because we assume at the higher production volume of 100 s it is brought down)

[a] The cost data are near term and mainly from previous research [21], which is derived by fitting industry data points to mathematical functions. The MCFC cost is consistent with the information from other sources such as the information obtained through personal communication with MCFC customers.

Table 6
Specifications of the base case 300 kW tri-generation system.

	System specifications
MCFC stack capacity, kW	300
Fuel utilization	70%
Fuel H_2 production capacity, kg d^{-1}	144
Hydrogen storage, kg of H_2 (determined based on fuel H_2 production capacity)	144
Maximum number of vehicles supported	151 (based on the average daily H_2 consumption of an FCV and a refueling station capacity factor of 0.63 [22])
Maximum H_2 Purification rate, kg h^{-1}	5.99
Maximum Compressor flow rate, kg h^{-1}	5.99
Number of dispensers	2 (two dispensers are provided for more reliable service)

In this study, the tri-generation system is assumed to be grid connected and enrolled in a Net Metering Program. Participating in the Net Metering program allows the tri-generation system to import and export electricity from and to the grid.

Based on US Environmental Information Administration (EIA) online data, nearly all states in the US are participating in Net Metering as of October 2012. However, the methods used to calculate and apply credits for exporting electricity to the grid vary among states and even within a state. Some utilities may also have certain limits on the maximum power the customers can export to the grid at any time.

In this study, we assume the Net Metering program has a 100 kW limit on the power the customers can export to the grid at any time, and the electricity exported to the grid is credited based

Table 7
System cost for the 300 kW tri-generation system (in 2012 dollars, based on equations in Table 5).

Component	Cost, \$
MC fuel cell	1,046,975
Co-generation heating system	65,436
H_2 purification (e.g., PSA unit)	87,485
Storage system, cascade system	240,630
Compressor	71,355
Dispenser	97,365
Electrical equipment	55,827
Safety equipment	13,087
Mechanical and piping	26,174
Non-equipment	151,345
Total cost	1,855,680
Maintenance cost	40,880

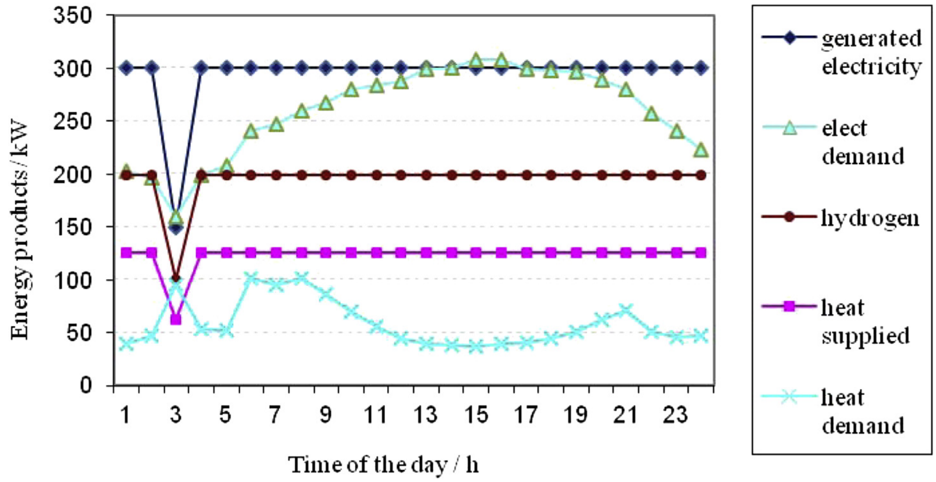

Fig. 6. Example daily operation of the 300 kW tri-generation system.

on a price 10% lower than the time of day retail price excluding demand and access charge (considering the demand and access charge, this rate is about 30% lower than the 13.1 ¢ kW h^{-1} annual average grid price). In addition, the credit customers receive for exporting electricity will never exceeds their grid electricity cost. These assumptions are important to model a realistic utility environment and to avoid disruption to the grid.

In this study, we assume the tri-generation system automatically operates at 50% or 33% load to meet the 100 kW Net Metering limit when the electricity load is more than 100 kW lower than the MCFC capacity. Without this 100 kW Net Metering limit, the tri-generation system would generate electricity at full capacity at all times and export all surplus electricity to the grid, so long as the owner can get credit for exporting electricity. In Section 4.4.1 how a tri-generation system operates will be further explained using an example.

4.4. Results and discussion

4.4.1. Base case results

Current high temperature FC systems such as MCFC systems targeting grocery stores are typically at the range of 300 kW–400 kW. Considering the fact that the average hourly electricity load in Table 1 is around 300 kW, we start with analyzing a 300 kW MCFC system. Later in this paper, we will evaluate the impact of varying the system size.

We assume the base case is a 300 kW tri-generation system under the energy demand data, energy price, and other engineering and economic inputs in Sections 4.1 and 4.2. The specifications and costs of the 300 kW tri-generation system under these assumptions are presented in Tables 6 and 7, respectively.

Fig. 6 is generated by the HTS model and illustrates the system operation by demonstrating the 24 h operation of the 84th day of the year as an example. This particular day is chosen because it is the first day of the year (starting at the first hour of Jan. 1st) in the hourly electricity profile that requires the system to operate at 50% load to assure that the electricity exported to the grid will not exceed 100 kW. The system is grid-connected, so electricity demand can be met from either the MCFC or the grid. If the electricity load is higher than 300 kW, the MCFC will be operating at 300 kW, and electricity demand above 300 kW will be purchased from the grid. If electricity load is in between 300 kW and 200 kW (300 kW minus the 100 kW net metering limit), the MCFC will be operating at 300 kW, and surplus electricity produced by the tri-generation system will be exported to the grid. If electricity load is in between 50 kW and 200 kW, the tri-generation system will automatically operate at 50% load (150 kW), and the same net metering restrictions apply.

For this particular day, the tri-generation system needs to operate at 50% load for only 1 h (hour 3). In this hour the heat supplied is less than the heat demand, and the hot water tank is assumed to accommodate this short period of mismatch. For other hours of the day, the heat supply is above the heat demand, and the excess heat is discarded through the pipes. The annual total electricity generated is 2,596,650 kW h. The electricity exported to the grid is 123,852 kW h, and purchased electricity is 334,136 kW h. The annual H_2 produced is 51,860 kg (142 kg d^{-1}). The system can support 150 vehicles.

Model results show that tri-generation is economically competitive in the base case with a LEC of 4.1 ¢ kW h^{-1}, which is 9 ¢ kW h^{-1} lower than the 13.1 ¢ kW h^{-1} annual average grid electricity price. The total annual grid electricity cost (BAU) is \$316,945, and the base case represents an annual electricity cost saving of 68.8%, or \$218,137.

Fig. 7 shows the contribution of each component to the LEC and the annual cost and revenue of tri-generation and the BAU case. The cost of purchased NG for heat in the BAU case is \$8208 and is quite small relative to the purchased electricity cost. H_2 fuel sale, capital, and NG feedstock cost are the biggest contributors to the LEC of tri-generation.

The total annual energy costs in the BAU case (i.e., purchase electricity and NG for heat from the utility) is \$325,153, while the base case tri-generation net annual energy costs (i.e., capital and operating costs) is \$497,373. As shown in Fig. 7, the revenue from H_2 fuel sale offsets a significant portion of costs, and contributes to the economic competitiveness of the tri-generation system. However, the revenue from H_2 fuel sale is sensitive to both the retail price and quantity of H_2. Sensitivity analysis on the LEC to H_2 fuel sale price and quantity is presented in Section 4.4.2 [5].

4.4.2. Sensitivity analysis

Energy prices and capital cost are subject to uncertainty; therefore sensitivity analysis is conducted by varying these inputs.

[5] H_2 fuel tax is not considered in this study. If H_2 is taxed, less revenues from the H_2 sale will be available to offset costs. The MCFC efficiency used in this study is significantly lower than the efficiency claimed by Fuel Cell Energy, which is a leading company for MCFC products. However, they hold the information proprietary making it not appropriate to use their numbers. With higher MCFC efficiency the NG feedstock cost will be reduced.

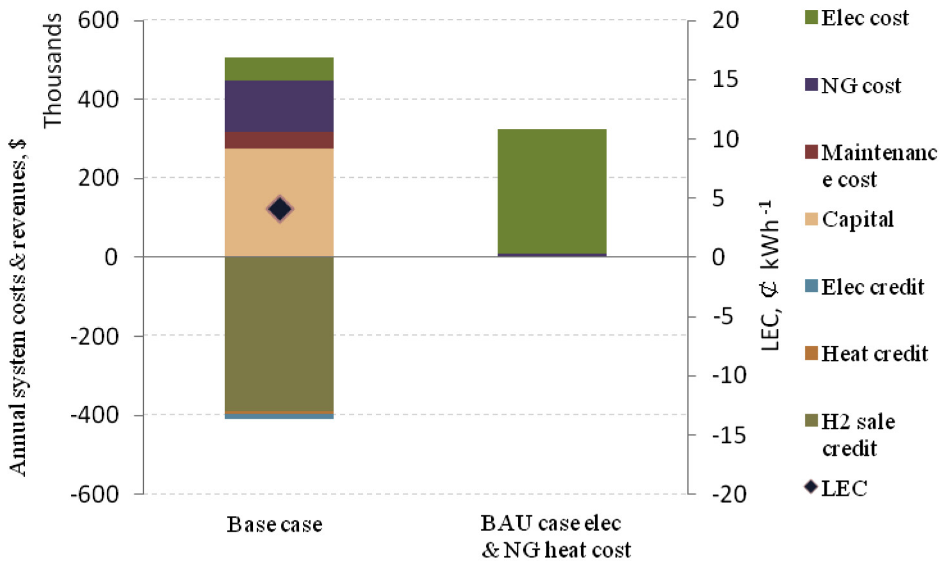

Fig. 7. Base case system costs, revenues, and LEC in comparison with the BAU case energy cost.

Model results show that increasing the NG price by 40% (which is equivalent to using the commercial NG price instead of the electricity generation NG price) leads to a LEC of 6.2 ¢ kW h^{-1}, which is still 6.9 ¢ kW h^{-1} (51%) lower than the 13.1 ¢ kW h^{-1} average grid electricity price. The resulting annual grid electricity cost saving is $168,074.

In Equation (1), revenue from H_2 sale is incorporated as credit. A higher H_2 price brings more credit. In the base case, the H_2 price is assumed to be $7.52 kg^{-1}, which is equivalent to the $4.1 $gallon^{-1}$ gasoline price in this study on a $ per mile basis. Reducing H_2 price to the $6 kg^{-1} target cost (equivalent to a $3.27 $gallon^{-1}$ gasoline price) of the US department of Energy in 2020[6], the resulting LEC is 7.3 ¢ kW h^{-1}, which is 5.8 ¢ kW h^{-1} (43.5%) lower than the 13.1 ¢ kW h^{-1} average grid electricity price. If we fix the LEC in Equation (1) as 13.1 ¢ kW h^{-1} average grid electricity price, the breakeven levelized H_2 cost is $2.86 kg^{-1}, which is well below the $6 kg^{-1} target cost of the US department of Energy in 2020.

Currently, there is a $2500 per kW self-generation credit in California, for which fuel cell systems are eligible. For a 300 kW tri-generation system, there will be a $750,000 self-generation credit that can offset part of the $1,855,680 upfront capital cost. This credit is also equivalent to a 40% reduction in capital cost, which can be from factors such as technology improvement and/or higher production volume. Model results show that with $750,000 reduction in capital cost, the resulting LEC is −0.5 ¢ kW h^{-1}. This result indicates that the system owner not only gains free energy, but also some profit. The annual total energy cost saving plus profit is $328,299.

In the base case, 142 kg of H_2 is produced daily, and the tri-generation system can support 150 vehicles. This is significantly less than the production level of a typical fuel only station. For example, the US Department of Energy H2A analysis assumes 1500 kg d^{-1} production level for stations in several cases studies. However, it is still possible that early H_2 demand would be lower than 142 kg d^{-1}. In order to understand the economic performance of tri-generation system with lower H_2 demand. We run the model with higher fuel utilization of 80% for electricity (vs. 70% in the base case), which means less NG is converted to H_2 fuel (20% vs. 30%). Model results show that with this lower level of H_2 production (83 kg d^{-1}), the resulting LEC is 10.1 ¢ kW h^{-1}. The H_2 sales income decreases, and the LEC is 3 ¢ kW h^{-1} (22.9%) lower than the 13.1 ¢ kW h^{-1} average grid electricity price. The resulting annual grid electricity cost saving is $72,419.

With more FCVs on road, the stores can produce more H_2 using lower fuel utilization for electricity. With 60% fuel utilization for electricity, the resulting LEC is −2.7 ¢ kW h^{-1}. H_2 production is 221 kg d^{-1}. H_2 sales bring significantly more income, and the LEC is 15.8 ¢ kW h^{-1} (121%) lower than the 13.1 ¢ kW h^{-1} average grid electricity price. The annual total energy cost saving plus profit is $381,406.

Fig. 8 shows the contribution of system costs and revenues to the LEC in the base case and the sensitivity analysis cases.

4.4.3. Results with varying system size and searching for the optimal size

The optimal size of a tri-generation system, defined as the size of the tri-generation system that minimizes total energy costs (including purchased electricity and NG) or maximizes revenue from the owner's perspective, is of interest to manufacturers and adopters. In this study, we conducted a brute force exhaustive search for the optimal size around the range of electricity load throughout the year. The life cycle (10 years) cost of each size within the search range is calculated in order to identify the optimal size.

Fig. 9 shows the LEC results with varying system sizes with base case engineering inputs, energy prices, and cost assumptions. The optimal LEC occurs around a broad minimal range of 320 kW–390 kW. There is a kink in the minimal range, which is caused by the restrictions on Net Metering participation explained in Section 4.3. The optimal LEC is around 2.8 ¢ kW h^{-1}, and is 1.3 ¢ kW h^{-1} (31.7%) lower than the 300 kW base case tri-generation system. In order to maximize the financial gains, the tri-generation system needs to be carefully designed, and there is clearly a tradeoff between the portion of electricity demand covered and the capital cost increase of bigger system size.

4.4.4. The CO_2 emissions of tri-generation systems

A tri-generation system provides three energy products. Therefore, when estimating and comparing emissions one should

[6] http://cafcp.org/progress/technology/doetargets.

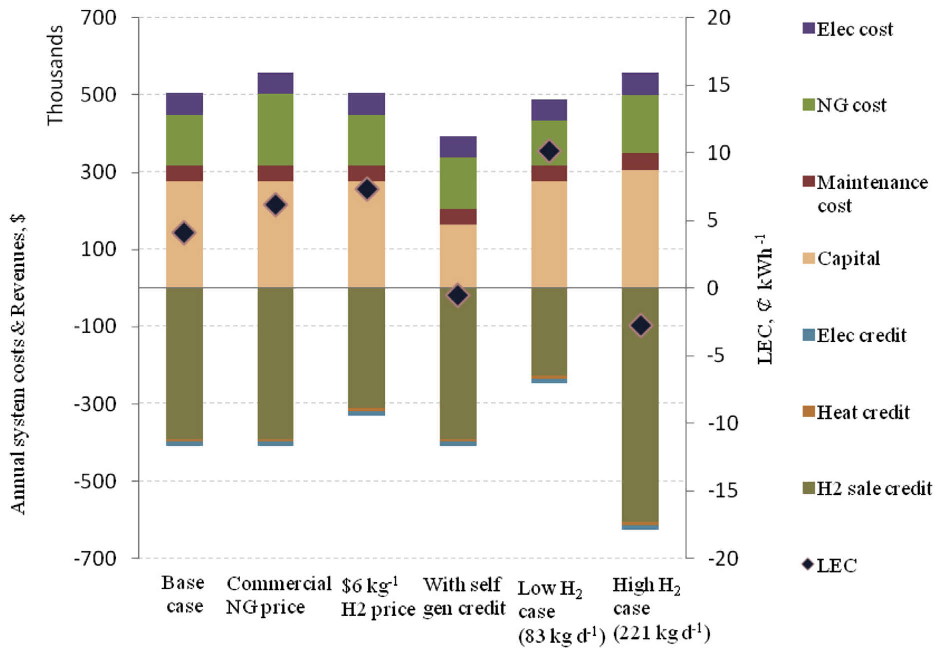

Fig. 8. The contribution of system costs and revenues to the LEC.

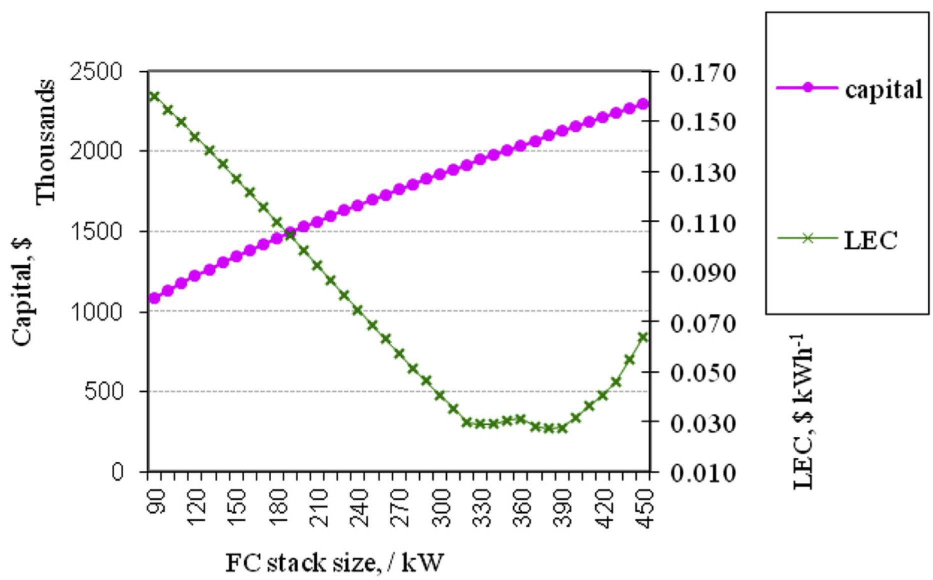

Fig. 9. Capital and LEC results of varying system sizes.

consider the emissions associated with meeting the three demands: electricity, heat, and transportation fuel. The CO_2 emissions from tri-generation to meet the three energy demand is compared with the BAU cases, in which the customers purchase grid electricity, NG combusted heat, and sell equivalent amount (on total miles traveled basis) of gasoline with market price. The electricity mix in both California and US is considered. This study compares the CO_2 emissions among 6 cases:

- Case 1 (base case) is MCFC tri-generation using NG as feedstock;
- Case 2 is tri-generation using NG for 2/3, and bio-methane for 1/3 of its feedstock;
- Case 3 is the BAU case with CO_2 emissions from grid electricity calculated using average California base load emission rate;
- Case 4 is the BAU case with CO_2 emissions from grid electricity calculated using average California grid non-base load emission rate;
- Case 5 is the BAU case with CO_2 emissions from grid electricity calculated using average US grid base load emission rate;

Table 8
CO_2 emission rates for electricity generation.

	CO_2 emission rates
NG weighted national average [23]	181 kg MWh^{-1}
Avg. CA grid, base load [24]	299 kg MWh^{-1}
Avg. CA grid, non-base load [24]	451 kg MWh^{-1}
Avg. US grid, base load [24]	552 kg MWh^{-1}
Avg. US grid, non-base load [24]	706 kg MWh^{-1}
Motor gasoline [23]	8.91 kg gal^{-1}

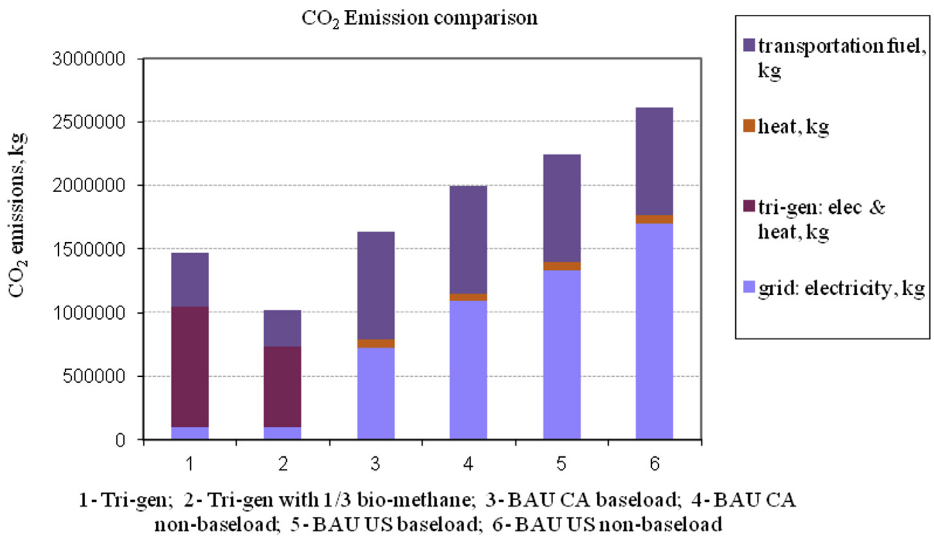

Fig. 10. Emissions with given heat demand.

- Case 6 is the BAU case with CO_2 emissions from grid electricity calculated using average US grid non-base load emission rate.

The emission rates used for the calculation are presented in Table 8, and the emission results for the 6 cases are summarized in Fig. 10.

Using tri-generation and NG (case 1, or base case) has lower CO_2 emission than all the BAU cases. The percent changes are 9.7%, 26.3%, 34.3%, and 43.6% relative to cases 3, 4, 5, and 6, respectively. The tri-generation case outperforms all the BAU cases in terms of total CO_2 emission from all the three energy products.

California Senate Bill 1505 requires that at least 33.3% of "the hydrogen produced for, or dispensed by fueling stations that receive state funds be made from eligible renewable energy resources". If 33.3% of the NG feedstock in the base case (case 1) is replaced with bio-methane or other renewable methane to meet this requirement as in case 2, there will be reductions of 37.8%, 49.2%, 54.7%, and 61.2% in CO_2 emission relative to cases 3, 4, 5, and 6, respectively.

One fact is worth noting when comparing the base case and case 3 (the California base load case). If we exclude transportation fuels, both H_2 for FCVs in the base case and gasoline for gasoline vehicles in case 3, the electricity and heat portion of CO_2 emission from tri-generation exceeds the grid electricity and NG heat portion of CO_2 emission in case 3. This is because the electricity mix in California is among the least carbon intensive in the country (more than half of the electricity in California is from renewables and nuclear, most of the rest is from NG plant, and only a small portion is from coal).

This result has important implications. That is, high temperature FC co-generation systems using NG feedstock, which are commercially available, can play a role in CO_2 emission reduction in low carbon electricity states such as California by replacing coal plants and non-base load electricity generation, but at best it will not offer significant CO_2 reduction by replacing current base load electricity generation plants in low carbon electricity states like California. Adding H_2 fuel for transportation to these co-generation systems changes the CO_2 emission status in the favor of FC, in that H_2 is produced as by-product in high temperature FC tri-generation system, and the efficiency for H_2 fuel production is high.

The pathway of injecting bio-methane or other renewable methane into existing NG infrastructure and utilizing high temperature FC tri-generation systems to simultaneously provide electricity, heat, and H_2 fuel seems highly attractive, from a CO_2 emission perspective.

5. Conclusions

In this paper, efficiency accounting methods and parameters for MCFC tri-generation systems have been developed. Interdisciplinary analysis and an engineering/economic model were applied for exploring the optimal design and evaluating the technical, economic, and environmental performance of distributed MCFC tri-generation systems. The analysis and engineering/economic model links energy demand side management, process engineering modeling, full fuel cycle economic and emission analysis, and policy analysis together, which allows a better understanding of the current performance of tri-generation technology, critical issues for improvement and how to accelerate the commercialization of these technologies.

Model results show that tri-generation is economically competitive with the current system, in which the stores purchase grid electricity and combusted NG heat. The LEC of the 300 kW base case tri-generation system is around 4.1 ¢ kW h^{-1}, which is 9 ¢ kW h^{-1} (68.7%) lower than the 13.1 ¢ kW h^{-1} annual average grid electricity price. There is a 68.8%, or $218,137 reduction in total annual grid electricity cost for adopting tri-generation.

The results are robust based on sensitivity analysis taking into consideration the uncertainty in energy prices and capital cost. For instance, increasing the NG price by 40% leads to a LEC of 6.2 ¢ kW h^{-1}, which is still 6.9 ¢ kW h^{-1} (51%) lower than the average grid electricity price. Lower H_2 price brings less income, and thus decreases the competitiveness of tri-generation. Reducing H_2 price from $7.52 kg^{-1} in the base case to the $6 kg^{-1} target cost of the US department of Energy in 2020, the resulting LEC is 7.4 ¢ kW h^{-1}, which is 5.7 ¢ kW h^{-1} (43.5%) lower than the average grid electricity price. Fixing the electricity price as 13.1 ¢ kW h^{-1}, the breakeven levelized H_2 cost is $2.86 kg^{-1}, which is well below the $6 kg^{-1} target cost. Tri-generation makes economic sense at low H_2 demand (83 kg d^{-1}), and higher H_2 demand brings significantly more income. The sensitivity of tri-generation performance to energy demand across regions is not evaluated due to data availability. This can be investigated in future study.

Varying system sizes with base case engineering inputs, energy prices, and cost assumptions, we found the optimal LEC occurs around a broad system size range of 320 kW–390 kW. Systems in

this size range do not meet peak electricity demands but may have a net export of electricity to the grid. There is a clear tradeoff between the portion of electricity demand covered and the capital cost increase of bigger system size.

MCFC Tri-generation systems offer favorable economics on capital investment in hydrogen refueling infrastructure because they have high overall efficiency and co-produce electricity and heat. These valuable co-products help address the low utilization problem typically encountered by hydrogen refueling stations when hydrogen vehicle demand is low. The continuous demand for electricity and heat in a building significantly reduces the financial risk associated with providing refueling infrastructure for early hydrogen fuel cell vehicle adopters. For a MCFC tri-generation system, its FC is a reformer, and an external fuel reforming system is not required.

MCFC Tri-generation technology also provides low emission electricity, heat, and H_2 fuel. The CO_2 emission can be reduced by 10% up to nearly 100%, depending on how the grid electricity is generated and whether renewable methane is used. By injecting bio-methane or methane from other renewable sources to the existing NG pipes, the high cost of building a transport and distribution infrastructure for hydrogen fuel can be avoided.

There are several policy implications of the results:

- MCFC tri-generation would not require subsidy for providing H_2 fuel to consumers during the transition, when small capacity stations would be needed (the H_2 production of the system under study ranges from 83 kg d^{-1}–221 kg d^{-1}).
- Tri-generation offers the option of making use of existing NG pipes for transport, distribution, and delivery of renewable methane for distributed renewable H_2 fuel production and combined heat and power with relatively high combined efficiency (delivered energy efficiency: electricity plus heat and H_2 fuel, 60%–70%).
- MCFC tri-generation offers innovative opportunities to reduce CO_2 emissions. Although we have not analyzed air quality implications in this study, an additional benefit is that the criteria pollutants such as NO_x, SO_x, and PM_{10} from MCFC systems are nearly zero because of the non-combustion process.
- Net Metering program is important for distributed MCFC tri-generation, because it offers the flexibility to import and export electricity from and to the grid. This would allow the owner to gain more economic benefits depending on how the program is designed. The exported electricity credit in this paper is fairly small because we chose a significantly lower price (30%) for exported electricity and the Net Metering program is quite restrictive in terms of the amount of exported electricity and corresponding credit.
- MCFC tri-generation for commercial building electricity, heat, and H_2 refueling has the potential to be included in hydrogen infrastructure plans or portfolio infrastructure solutions in California and likely in other states or countries.

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